National Aeronautics and Space Administration

Bandwidth-Efficient Communication through 225 MHz Ka-band Relay Satellite Channel

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International Satellite Communication Systems Conference

Cleveland, Ohio

October 17-20, 2016

www.nasa.gov/exploration

- Current and Future NASA Communication Architecture

- High-rate Flight Experiment through Ka-band Relay

- Test Results

- Conclusions

NASA's Near Earth Relay Satellite System

- NASA's Tracking and Data Relay Satellite System (TDRSS) has multiple communication relay satellites in geostationary orbits, and provides continuous coverage to low-Earth orbiting spacecraft
  - Ku-band and Ka-band provide wideband (225/650 MHz), high data-rate channel for science data return
- NASA's use of Ka-band through relay satellites and direct-to-ground is expected to increase significantly in coming years
- Improved bandwidth efficiency and reduced user burden will aid transition to Ka-band

Single Access Antenna
- S, Ku, Ka-band
- 225, 650 MHz bandwidth
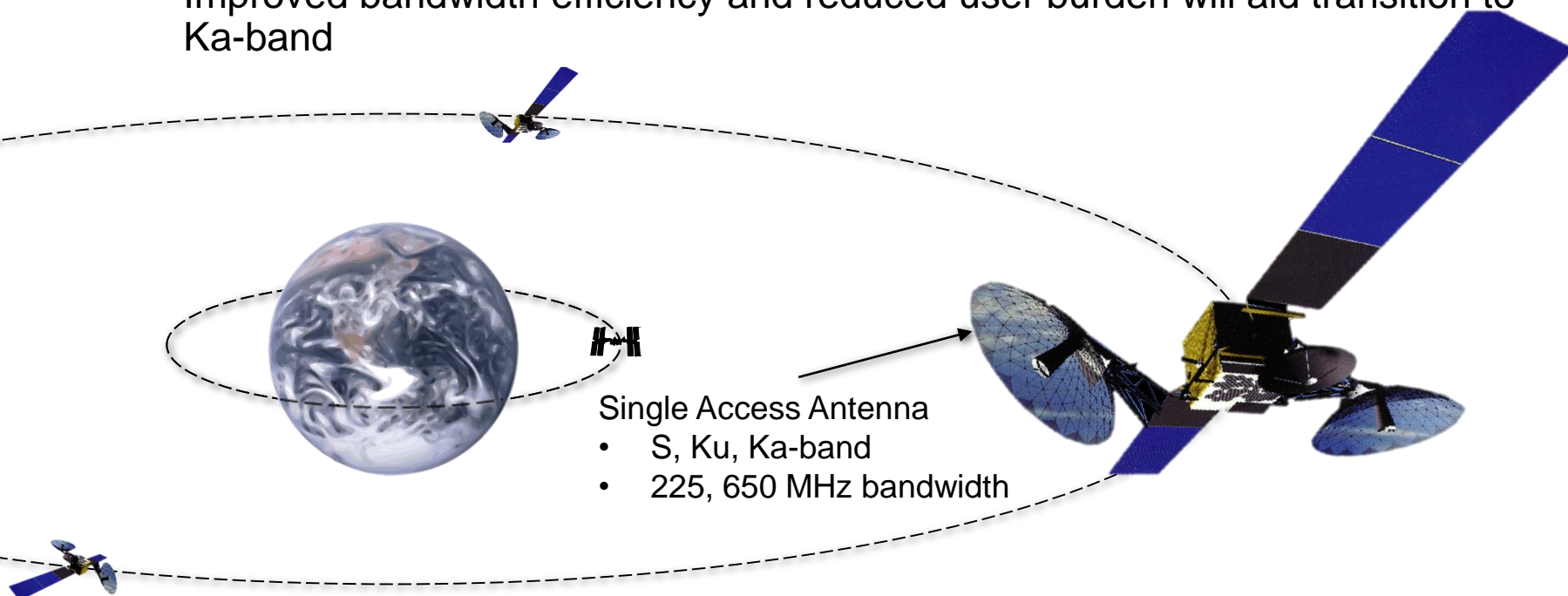
- **New/Enhanced Services Highlights**
  - Increased data rate (> Gbps)
  - Improved networking (IPv6 & delay tolerant networking (DTN)
  - On-demand, flexible service
  - Messaging/control service (multiple access)
  - Cognitive communications
  - Inter-agency service management based on CCSDS standards

- **Earth Network Architecture**
  - Full coverage network with relay orbiters in GEO & possibly other orbits
  - Mix of NASA, commercial, & international service providers
  - Ground/space assets for low end-to-end forward/return data latency
  - Optical ground telescopes provide continuous optical support
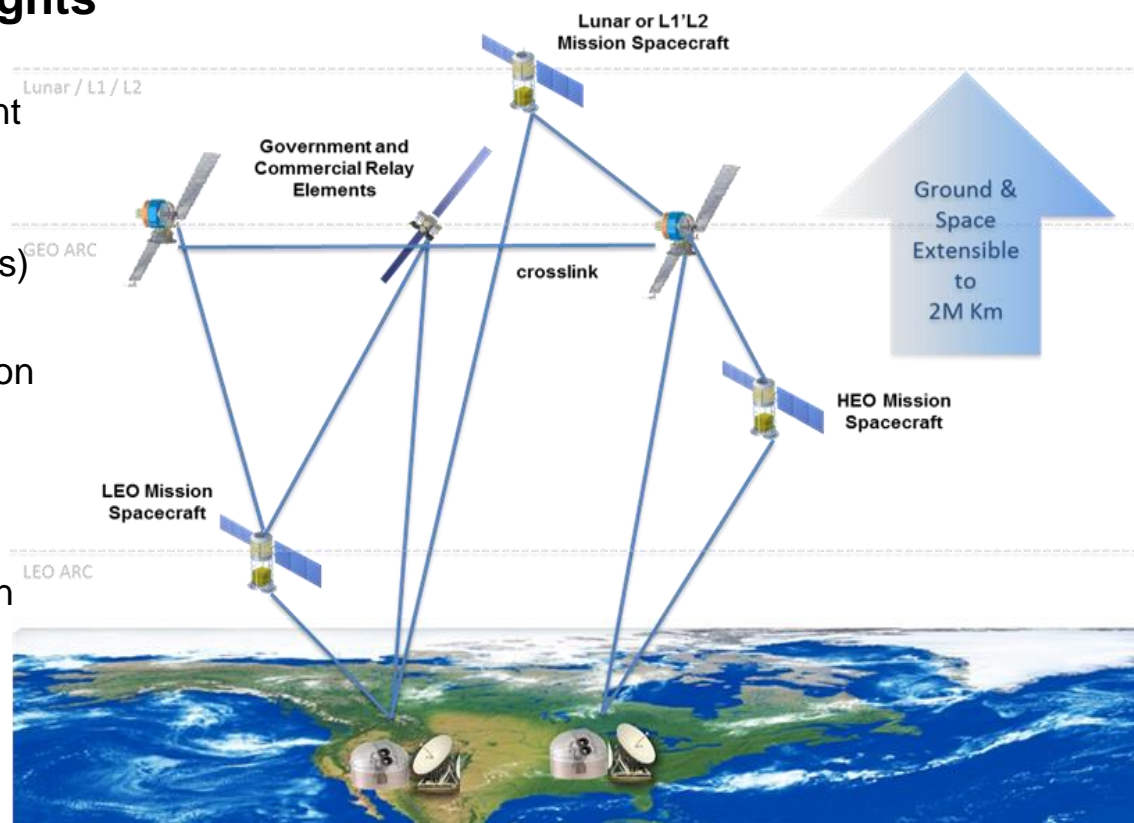

Notional Earth Architecture

Flight Experiment Objectives and Goals

- Maximize throughput over the 225 MHz Ka-band relay channel using bandwidth-efficient techniques
- Develop methods to compensate for gain and phase distortions over the bandlimited channel, including non-linear distortions from travelling wave tube (TWT) amplifiers

	Modulation	Code Rate	Data rate through 225 MHz (Mbps)
Current practice	OQPSK, Low-pass Filtered	1/2 7/8	100 262
Experiment goal	Precoded GMSK, (BT=0.3)	7/8	175
	OQPSK, (SRRC 0.2)	7/8	350
	8-PSK, (SRRC 0.2)	7/8	525
	16-APSK, (SRRC 0.2)	7/8	700
	32-APSK, (SRRC 0.2)	7/8	875
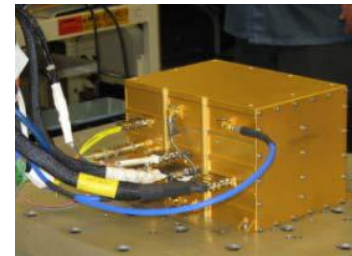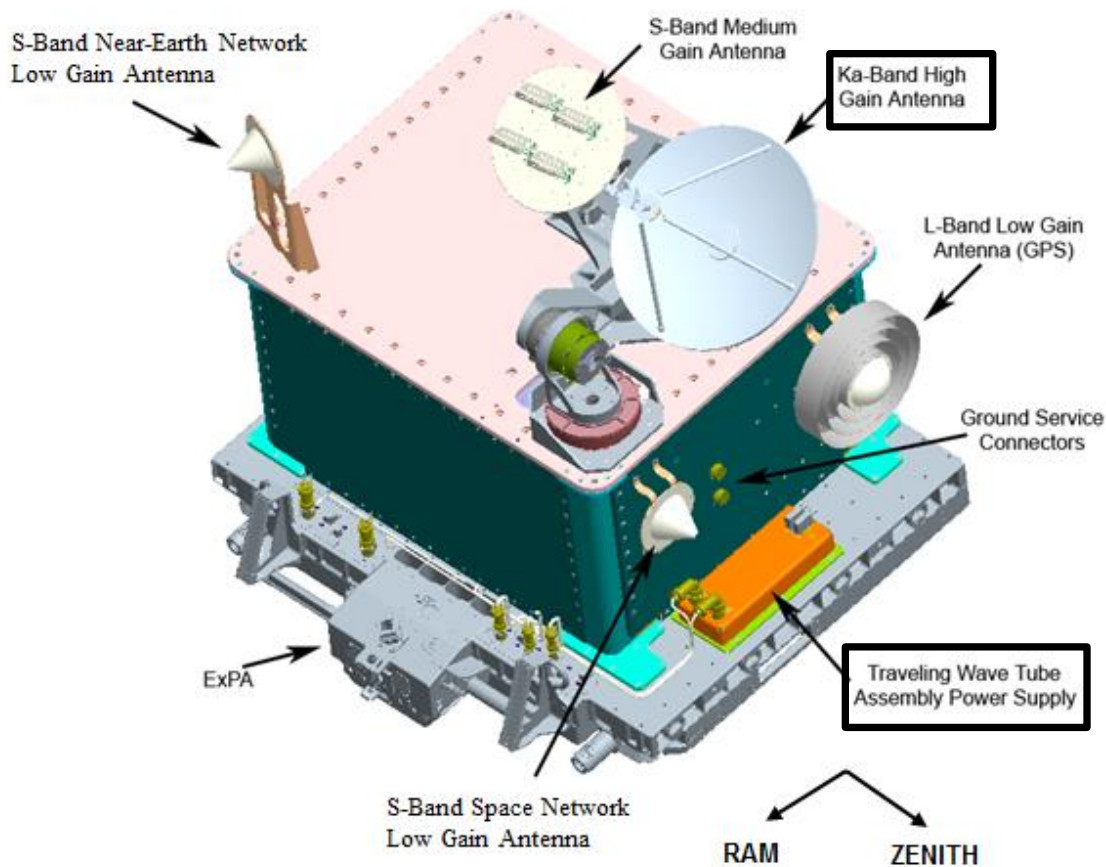
General Dynamics SDR
S-band Transceiver
(1) Virtex-2 FPGA
8W amp
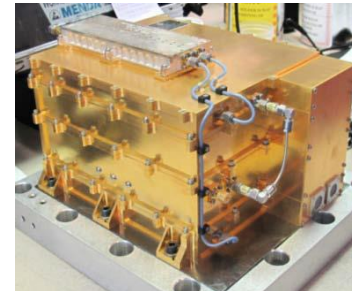
JPL / L3-CE SDR
S-band Transceiver,
L-band (GPS)
(2) Virtex-2 FPGAs
7W amp

Harris Corporation SDR
Ka-band Transceiver
(4) Virtex 4 FPGAs, DSP
40W TWTA

S-Band Near-Earth Network Low Gain Antenna

S-Band Medium Gain Antenna

Ka-Band High Gain Antenna

L-Band Low Gain Antenna (GPS)

Ground Service Connectors

Traveling Wave Tube Assembly Power Supply

ExPA

S-Band Space Network Low Gain Antenna

RAM   ZENITH

SCaN Testbed - Ka-band Sub-System

- Gimbaled, 46 cm Parabolic Dish Antenna
- Closed-loop tracking via received signal strength
- Traveling Wave Tube Amplifier (40W, 45% efficiency)

Parameter	Value
Frequency (GHz)	25.65
EIRP (dBW)	52.75
Channel Loss (dB)	212.59
Received Isotropic Power (dBW)	-159.84
TDRS G/T specification (dB/K)	23
Boltzmann's Constant (dBW/K/Hz)	-228.6
TDRS Ku-band Downlink C/N_0 (dB-Hz)	110.5
C/N_0 at Ground Station (dB-Hz)	91.71*

*Operational testing with SCaN Testbed has observed C/N_0 up to 99 dB-Hz, due to higher actual TDRS G/T

High-rate Bandwidth-Efficient Transmitter
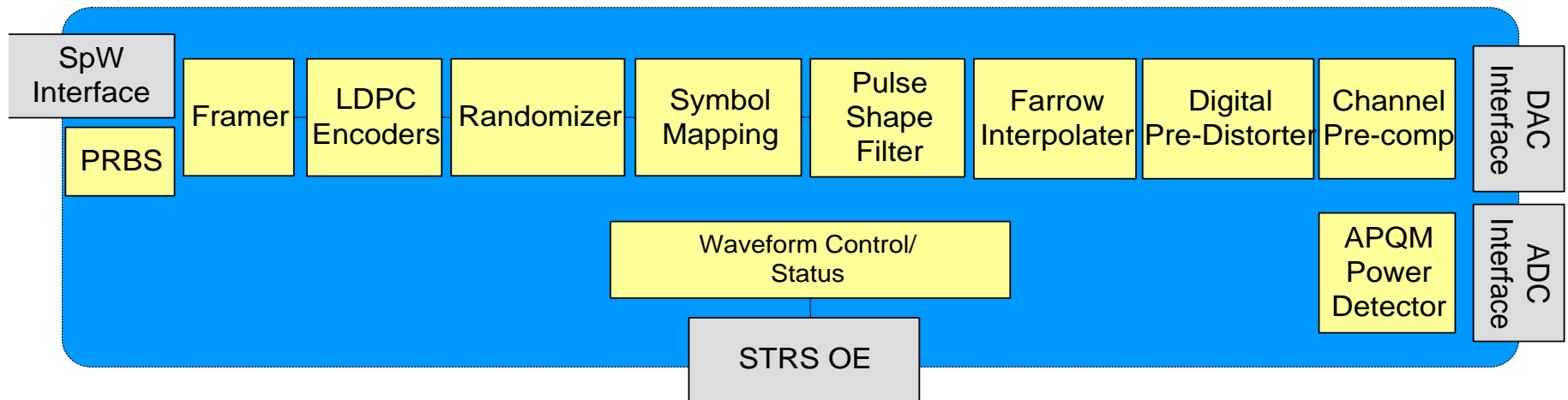
Modulation: GMSK, BPSK, OQPSK, 4/8/16-PSK, 16-QAM, 16/32-APSK

Data Rate: Adjustable, 1000 Mbps

Pulse-shape Filtering: 128-taps, SRRC and RC, various roll-offs

Forward Error Correction: LDPC, AR4JA ½, 2/3, 4/5, C2 rate 7/8

Framing: CCSDS Framing and Randomizer

Digital Pre-distortion: Memory-less, Symbol Pre-distortion

Channel Pre-compensation: 32-tap FIR

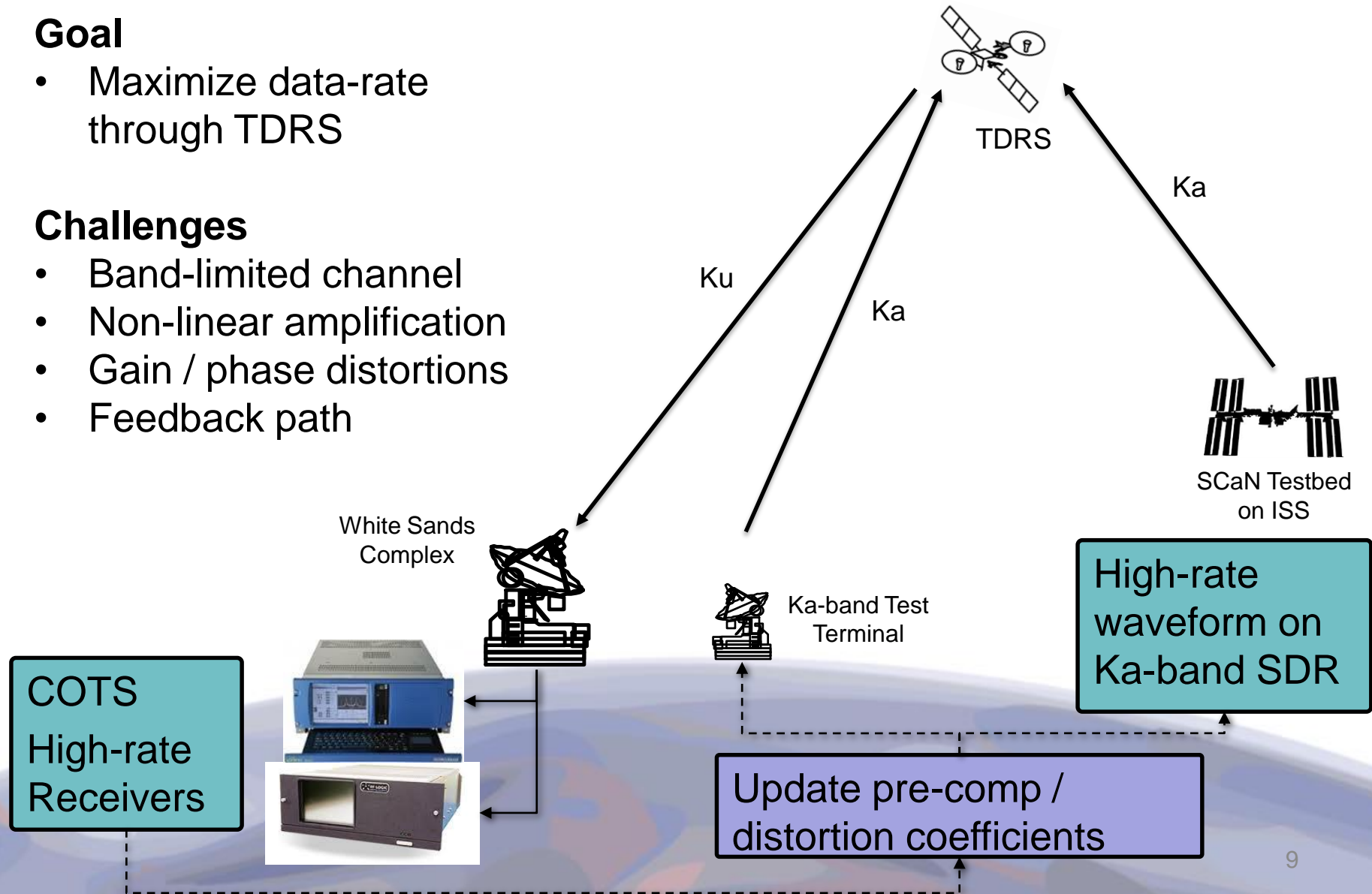*Waveform is available via STRS Repository: https://strs.grc.nasa.gov/*

Goal

- Maximize data-rate through TDRS

Challenges

- Band-limited channel
- Non-linear amplification
- Gain / phase distortions
- Feedback path

TDRS

Ka

Ku

Ka

SCaN Testbed on ISS

White Sands Complex

Ka-band Test Terminal

High-rate waveform on Ka-band SDR

COTS High-rate Receivers

Update pre-comp / distortion coefficients

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Results Summary

- Ka-band Test Terminal enabled near 700 Mbps over the 225 MHz channel, band limiting distortions limited full potential
- SCaN Testbed achieved 400-500 Mbps with 8-PSK, LDPC 7/8, power and bandwidth limited
  - Performance varied between TDRS satellites (2nd vs. 3rd generation) and dedicated versus composite signal configuration

| Modulation	Filter	Encoding	Ka-band Test Terminal	SCaN Testbed on ISS
GMSK	Gaussian, BT=0.3	Uncoded	200 Mbps*	
OQPSK	SRRC 0.2	LDPC 7/8	350 Mbps*	
8-PSK	SRRC 0.2	LDPC 7/8	525 Mbps (1e-10)	525 Mbps (1e-5)
16-APSK	SRRC 0.35	LDPC 7/8 LDPC 2/3	678 Mbps (1e-9) N/A	262.5 Mbps (1e-10) 433.3 Mbps (1e-8)

* Bit-error rate: 1e-12

- Substantial system loss as bandwidth increases.
  - Receiver adaptive equalizer not sufficient, pre-compensation required at transmitter
- Highest symbol rates were problematic for adaptive equalizers to track – better performance with custom filter matched to channel
  - Potential issue for operations at these bandlimited conditions – spacecraft may need to re-train matched filters on ground receiver throughout mission


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16-APSK, 75 MBaud (300 Mbps), without Digital Predistortion
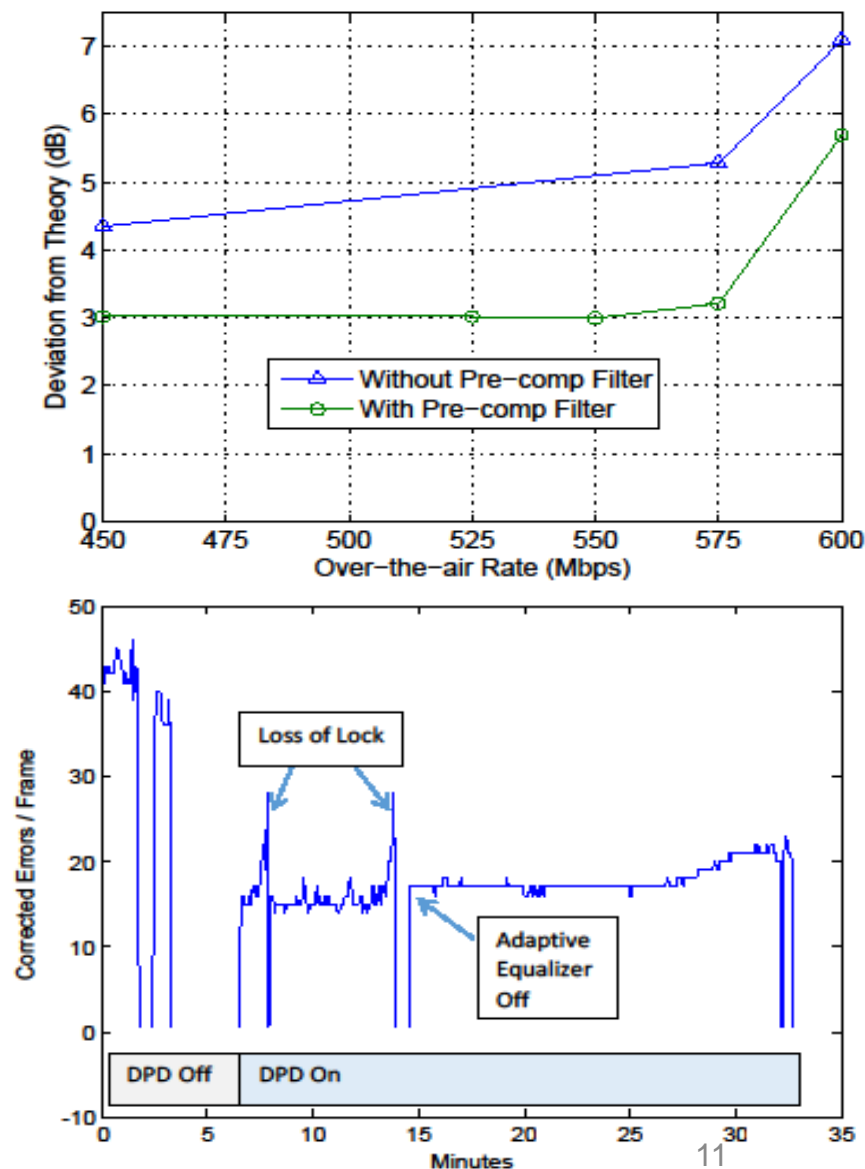
16-APSK, 75 MBaud (300 Mbps), Digital Predistortion
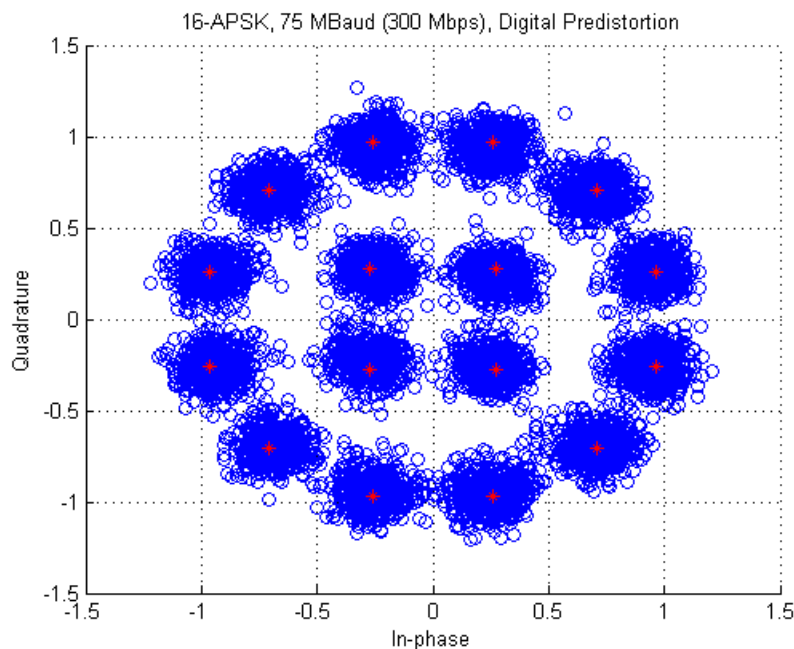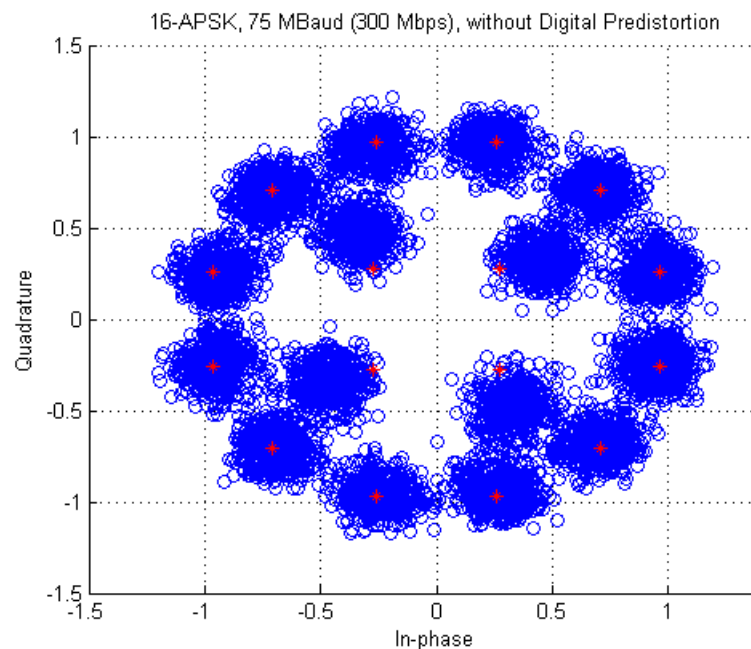
- Primary source of non-linear distortion is the user space-craft power amplifier (e.g. TWTA)

- Static symbol predistortion (adjusting amplitude ratio and the relative phase between the inner and outer rings)

- In-situ channel characterization – use measurements at ground receiver to automate channel correction

LDPC 7/8 coded 16-APSK at 525 Mbps User (150 Mbaud), CWER = 1e-6, SRRC α = 0.35
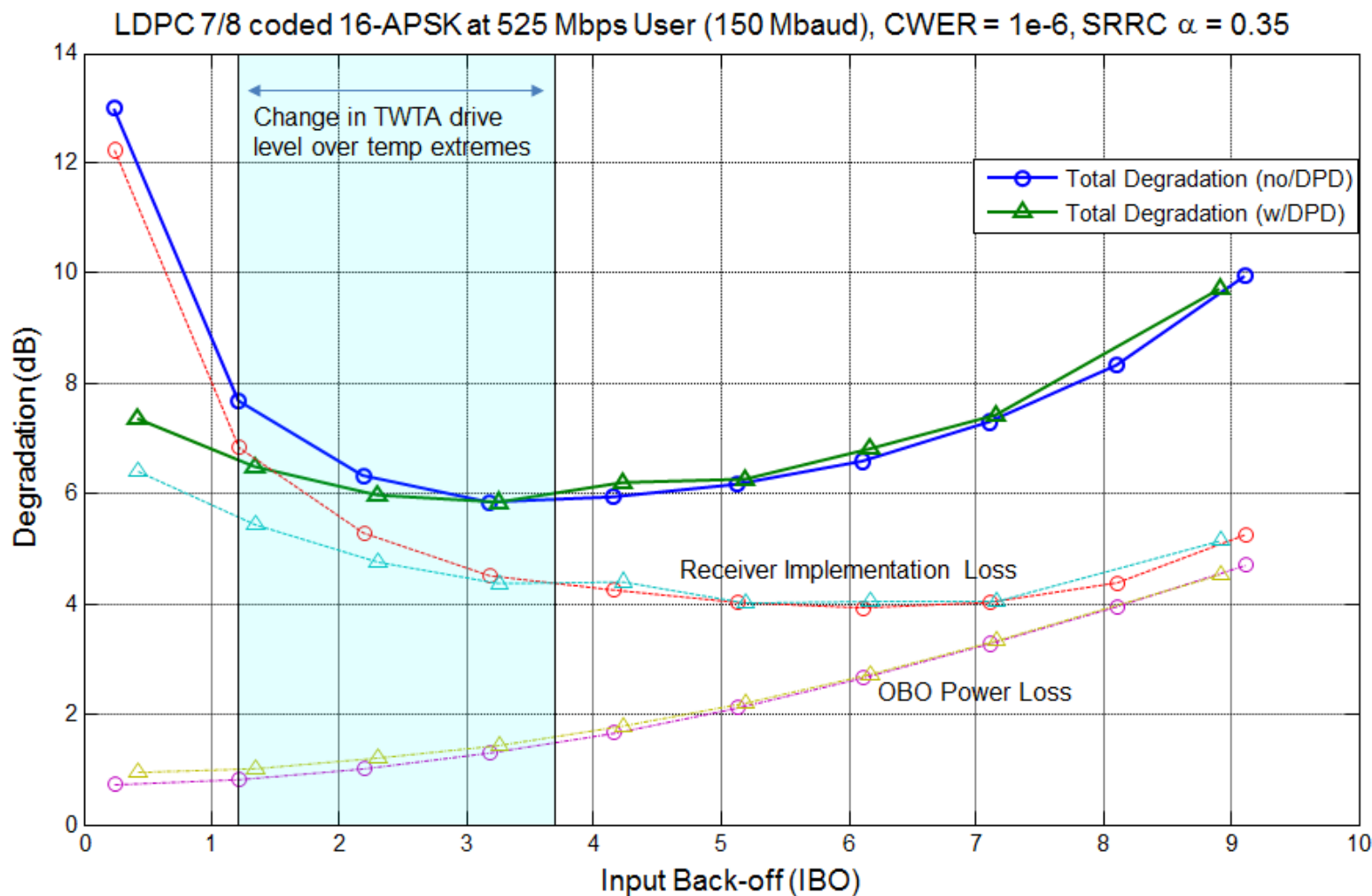
- Pre-distortion provided minimal gain 0-0.25 dB, depending on code rate
- Static pre-distortion was effective in improving performance and stability, especially near saturation point of amplifier

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Summary and Conclusions

- Demonstrated reconfigurable bandwidth-efficient waveforms

- Validated user data rates 700 Mbps over the 225 MHz channel, with 500 Mbps from space flight radio

- Demonstrated digital pre-distortion and pre-compensation techniques as companions for higher-order modulations

- Modulation waveform code in STRS repository for re-use

Backup

Next Generation SCaN Architecture Vision

- **"Shrink" the solar system** by connecting the principle investigator more closely to the instrument, the mission controller to the spacecraft, and the astronaut to the public

- **Improve the *mission's experience* and reduce *mission burden*** – the effort and cost to design/operate spacecraft to receive services from SCaN Network

- **Reduce *network burden*** – the effort and cost required to design, operate, and sustain the SCaN Network as it provides services to missions

- **Apply new and enhanced capabilities** of terrestrial telecommunications and navigation to space, leveraging other organizations' investments

- **Enable growth of commercial services** for missions currently dominated by government capabilities

- **Enable greater international collaboration** and lower costs in space by establishing an open architecture with interoperable services that can be adopted by international agencies and as well as NASA

Lunar Network · **Earth Network** · **Mars Network**
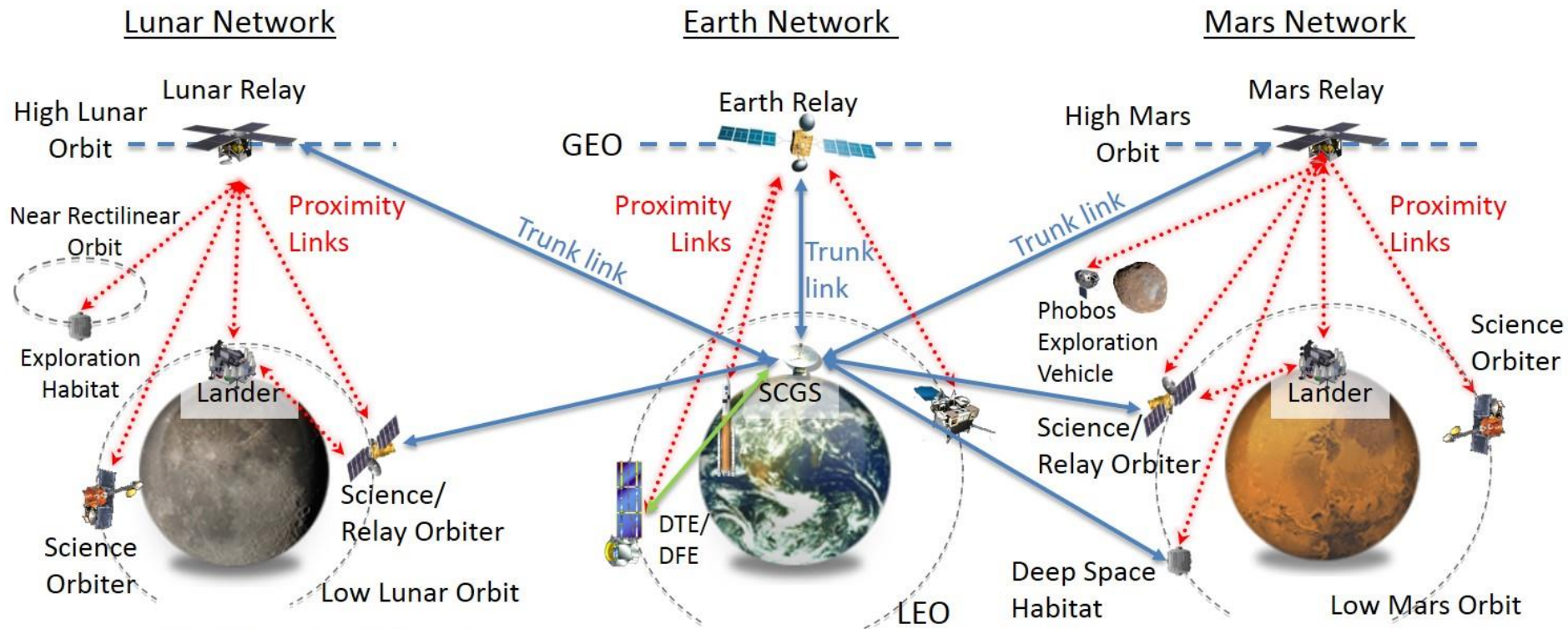
Benefits of Planetary Networks:
- Reduced mission burden with short links for in-system communications - enables in-system telerobotics
- Common architecture reduces technology & development costs
- Reuse of HW & SW: Family of products includes variants for different environments
- Reuse of spectrum

Architect for Flexibility, Scalability, & Affordability –
Implement as required to meet specific mission needs

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